

# The Impact of Climate Change on Material Degradation Criteria in Heritage over Iran: Regional Climate Model Evaluation

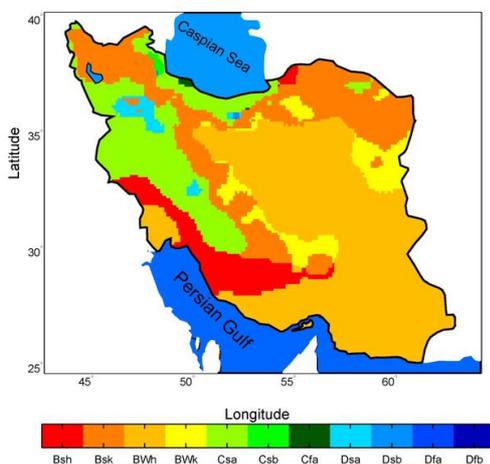
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**Abstract.** Understanding how climate change accelerates or slows down the process of material deterioration is the first step towards assessing adaptive approaches for the preservation of historical heritage. Analysis of the climate change effects on the degradation risk assessment parameters like salt crystallization cycles is of crucial importance when considering mitigating actions. Due to the vulnerability of cultural heritage in Iran to climate change, the impact of this phenomenon on basic parameters plus variables more critical to building damage like salt crystallization index needs to be analyzed. Regional climate modelling projections can be used to assess the impact of climate change effects on heritage. The output of two different regional climate models, the ALARO-0 model (Ghent University-RMI, Belgium) and the REMO model (HZG-GERICS, Germany), is analyzed to find out which model is more adapted to the region. So the focus of this research is mainly on the evaluation to determine the reliability of both models over the region. For model validation, a comparison between model data and observations was performed in 4 different climate zones for 30 years to find out how reliable these models are in the field of building pathology.

## 1 Introduction

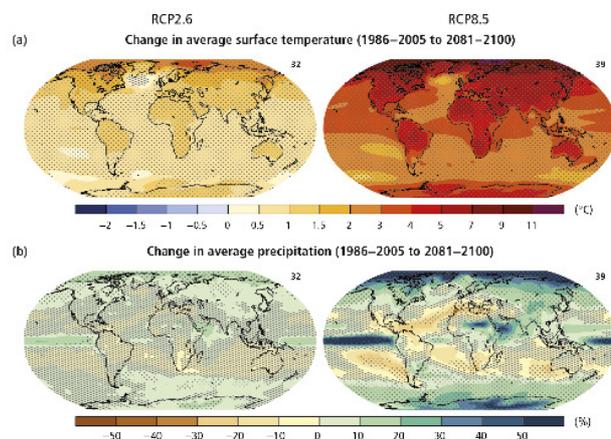
The Iranian plateau host one of the oldest civilization in the world. The country's rich cultural heritage is reflected in part by its 22 UNESCO world heritage sites. Having 11 climates (Fig. 1) out of the world's 13, Iran's climate is diverse, ranging from arid to subtropical along the Caspian coast and the northern forests.



**Fig. 1.** Climate map of Iran (Köppen-Geiger)

Fifth Assessment Report of the Intergovernmental Panel on Climate Change suggests significant changes in regional climate conditions during the next century, such as drier and hotter summers over the middle East, and Iran is located in this region (Fig. 2). Regional climate modelling experiments are typically based on a dynamical downscaling strategy e.g. [1]. At the top, there are runs with a General Circulation Model (GCM) to study climate conditions on a global scale. Nevertheless, the spatial resolution of such global simulations, typically more than

100 km, is too coarse to identify climate variability on a regional scale, e.g. resulting from orography.



**Fig. 2.** Change in average temperature and precipitation 1986-2100 [2]

Through Regional Climate Models (RCM), GCM data are downscaled to resolutions between 4-50 km across a specific region. Over some regions, e.g. Europe, large ensembles of RCM experiments are available whereas other regions, e.g. Central Asia, are rarely studied. Thus Within the framework of the AFTER project 2 different RCMs, ALARO-0 and REMO, are used for high-resolution climate projections over Central Asia as described by Kotova et al[3]. Recently Top et al. [4] evaluated the performance of both models over Central Asia by comparing the evaluation run with gridded observations. In this paper, both RCM experiments will be explicitly assessed over Iran to use them at a later stage to understand the impact of climate change on Iranian heritage degradation.

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## 2 METHODOLOGY

### 2.1 Model Analysis

Given that Iran has an extended range of rather extreme climate regimes, and models are not often used for such a climatic zone, these models need to be evaluated first. The RCM data in this analysis originates from the ALARO, and REMO models run at a spatial resolution of 25 km across the central Asia domain available at a time-frequency of 1-hour. The evaluation run, coupled to ERA-Interim at the boundaries of the CAS CORDEX domain, is used to investigate the quality of the model simulations. The evaluation run enables the possibility to evaluate whether the model can reproduce the climate conditions

The analysis will be based on a comparison of the modelled and observed meteorological parameters at four places, located in different climatic zones, in Iran:

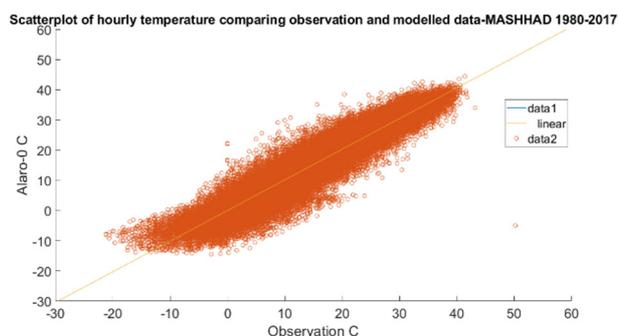
- **Mashhad**, which is located in the northeastern corner of Iran, features a steppe climate (Köppen/*Bsk*) with hot summers and cold winters.
- **Shiraz** is located in the south of Iran. Shiraz's climate is overall classified as a hot semi-arid climate (Köppen climate classification *BSh*).
- **Tabriz** is located in the northwest of Iran and has a humid continental climate with regular seasons (Köppen *Dsa*) bordering Cold semi-arid climate (Köppen *BSk*).
- **Rasht** is located on Iran's Caspian Sea coast, depending on the precipitation, Rasht either has a humid subtropical climate (*Cfa*) or a Mediterranean climate (*Csa*).

The selected locations have very long, consistent timeseries and will be compared to the historical model runs for the period 1980-2017. The discussed parameters are outdoor 2 m air temperature and relative humidity, and precipitation. Through the validation study, some climatic parameters which are likely critical for heritage like freeze-thaw cycles and salt crystallization index were evaluated for both models in comparison with the historical data to find out how reliable these models are in the field of building pathology.

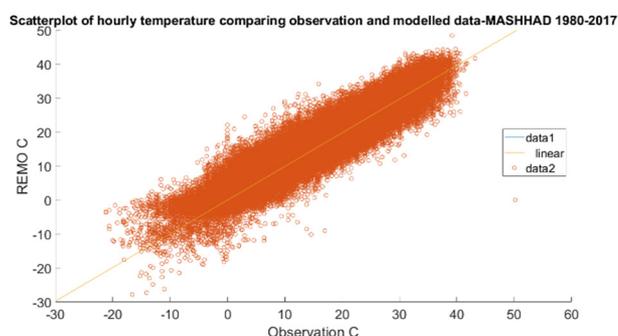
#### 2.1.1 Temperature Analysis

Analyzing the scatterplots indicates that there is a good overall representation of the observed hourly temperatures by both models almost in all locations (Fig. 3, Fig. 4). Both scatter, and distribution-histograms follow a similar pattern for each location, where the linear fit (blue) of the hourly temperature approximately follows the diagonal (perfect fit) and proves that the relation between models and observation is statistically significant. Besides, some coefficients which are critical in the model validation study, i.e. correlation and

Adjusted R-Squared had been calculated, and all of them confirm that both models perform well (Table 1). Analyzing the distribution chart gives us information on how the data is distributed. (Fig. 5). In mid-range temperatures, models have different behaviors where the ALARO has a lower amplitude in comparison with observations, and REMO has the most accumulation in this range.



**Fig 3.** Hourly temperature scatterplot ALARO model

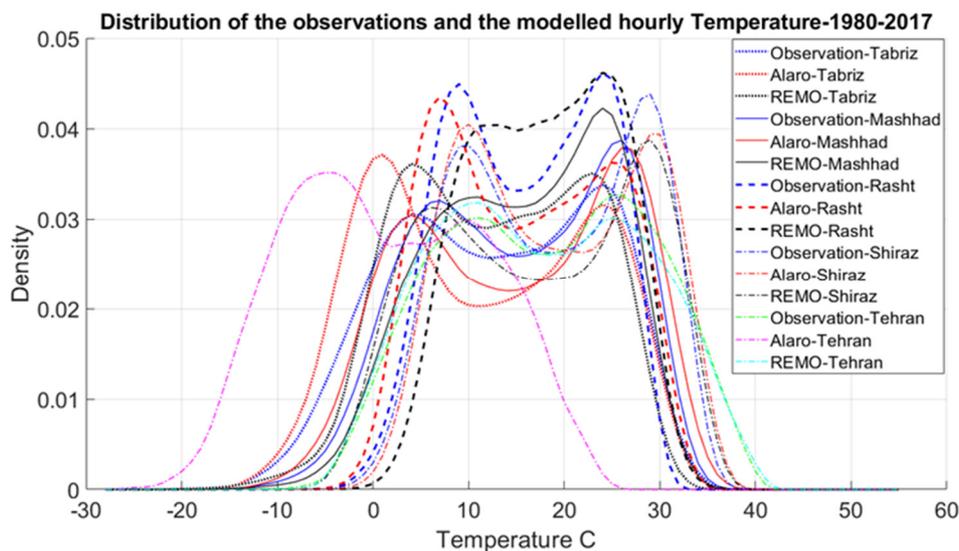


**Fig 4.** Hourly temperature scatterplot Remo model

The values of the observed and modelled  $T_{mean}$ ,  $T_{min}$ , and  $T_{max}$  over the whole period are summarized in Table 2. We can find that in the areas with specific climate conditions, e.g. Mashhad with a Steppe climate, the bias between observation and modeled data is smaller compared to areas that cannot be classified in just one climate zone, e.g. Rasht, where we can observe the most bias.

**Table 1.** Validation coefficients (based on 3-hour values)

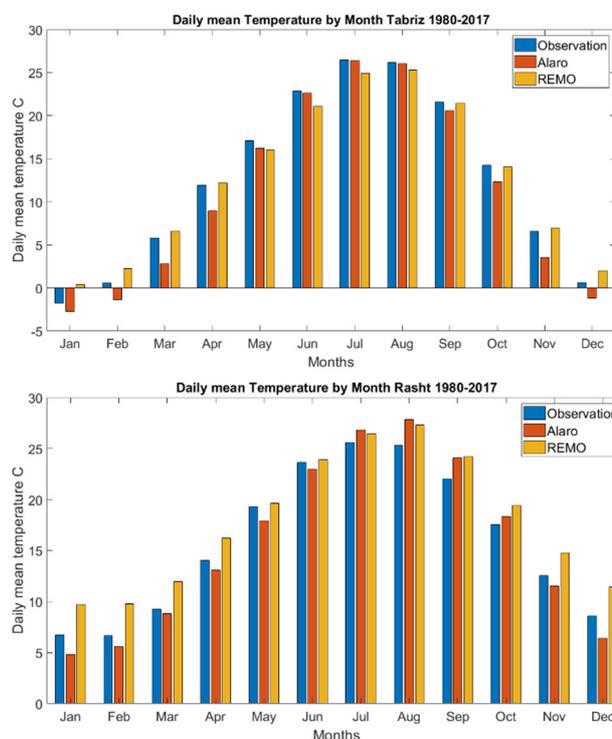
Daily mean temp.	Alaro Model		REMO model	
	Correlation	Adjusted R-Squared	Correlation	Adjusted R-Squared
Mashhad	0.96	0.93	0.95	0.92
Rasht	0.95	0.91	0.95	0.90
Tabriz	0.97	0.94	0.97	0.95
Shiraz	0.98	0.97	0.98	0.97



**Fig. 5.** Distribution of Average daily temperature over all locations.

The correlation and other coefficients in Table 1 confirm the statement that the reliability of both models in the same location (Rasht) is less than in other studied areas. These values are not in line with the conclusions based on the distribution, i.e. the underestimation of extreme minimum temperatures by REMO modeled data towards colder temperatures (Fig. 5). However, as these values are outliers, they are not expected to represent the temperature distribution.

By analyzing the monthly statistics (Fig. 6), it can be observed that the model yields a different pattern wherein during cold months, the REMO model has predicted warmer temperatures than observations and within summer months colder temperature. In contrast, the Alaro-0 model predicted colder temperatures than the observations during the cold months almost in all locations, and during summer months it has a positive bias noting that again in Rasht, the bias rate has been significantly adjusted in both models but follows the same pattern (Fig. 6).



**Fig. 6.** Comparison between monthly mean temperature. Tabriz (top) and Rasht (bottom).

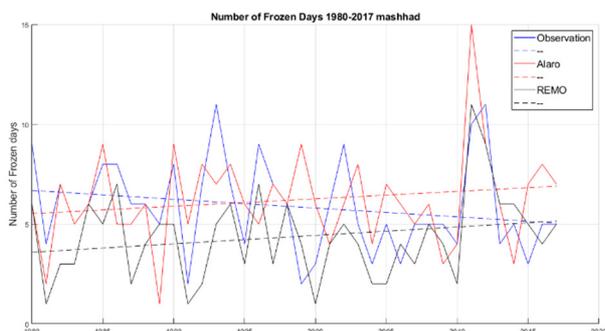
**Table 2.** Daily mean, max and min temperature comparison

Daily mean-min-max Temperature	Observation			REMO model			Alaro-0 Model			
	City	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min
Mashhad		15.03	43.2	-21.2	15.6	48.5	-28.8	15.1	44.5	-14.5
Rasht		13.91	38.80	-12.40	17.95	47.62	-19.42	15.75	42.21	-7.64
Tabriz		12.74	40.40	-19.40	12.81	41.90	-28.22	11.26	40.67	-16.76
Shiraz		18.81	42.6	-9.40	17.36	42.90	-10.06	19.02	47.81	-7.91

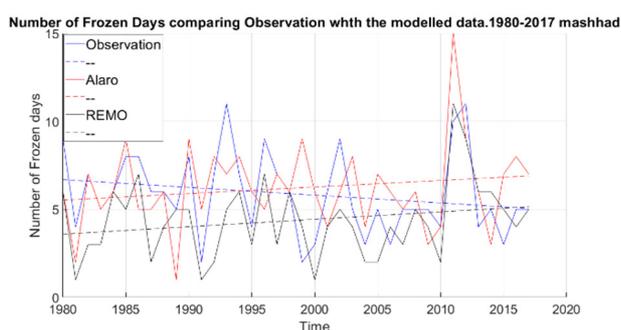
Besides statistics on hourly and daily  $T_{mean}$ , some interesting indices are useful in the field of building physics, such as indices on frost.

The first index is the number of freeze-thaw cycles (FTC), as described by Grossi et al [5].

Based on daily  $T_{mean}$ , one cycle is counted each time the temperature drops below  $0^{\circ}\text{C}$ , given that the previous day was a non-freezing day. Following, the difference in the annual number of FTC between the observations and the modeled data is computed. It can be noted that in contrast to the observations, both models follow an increasing trend in almost all locations (Fig. 7, Fig. 8).



**Fig. 7.** Number of FTC in models and observation. Mashhad.

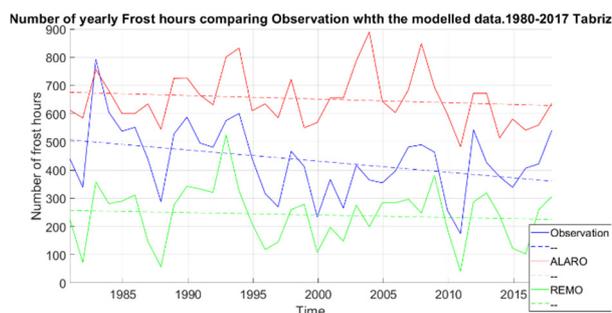


**Fig. 8.** Number of FTC in models and observation. Tabriz

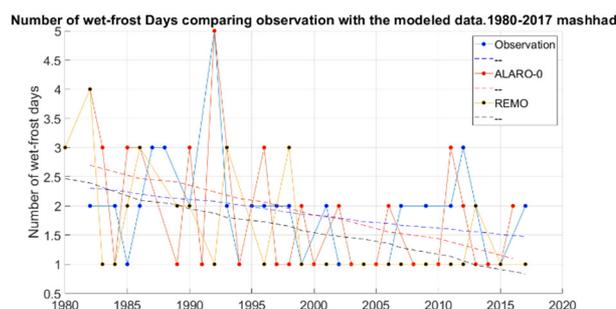
The hours of frost index, illustrated in Fig. 9, indicate the annual duration of freezing temperatures. Unlike the first index, in 2 locations the models and observations follow a similar trend despite the difference in the number of cycles. The REMO model almost in all areas has predicted considerably fewer frost hours in comparison with the ALARO-0 model and observations.

The previous indices are only based on temperature. However, frost damage in building envelopes is highly related to the moisture content in the porous media. The wet frost index considers the annual number of rainy days, i.e. the total daily precipitation exceeding 2 mm and temperatures higher than  $0^{\circ}\text{C}$ , immediately followed by days having a  $T_{mean}$  below  $-1^{\circ}\text{C}$  [6]. The wet frost index is generally higher for the ALARO model compared to the REMO model and more consistent with the observation (Fig. 10).

The number of freeze-thaw cycles over the area is not considerable, so the significant difference between the model trend slope and observation is negligible.



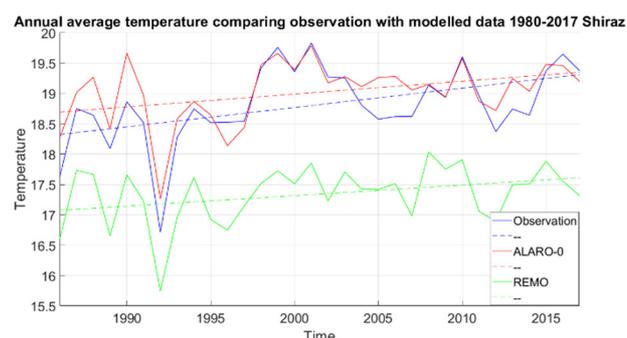
**Fig. 9.** Number of frost hours per year-Tabriz



**Fig. 10.** Wet-Frost cycles based on average daily temperature

Analyzing the trend lines and their slope is a critical and decisive step since it can determine the impact of the studied parameter on the future climate.

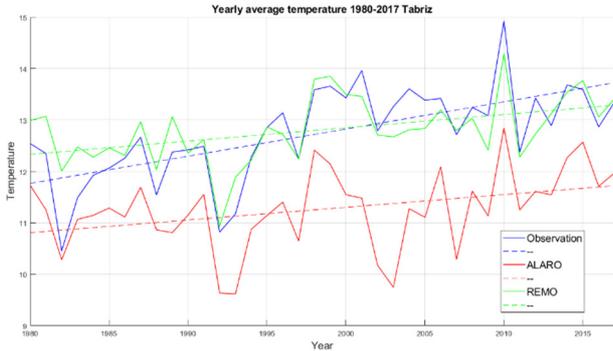
As it can be observed in all locations (Fig. 11, Fig. 13), both models following the observations have an incremental trend. The most substantial difference between the trend slopes can be observed in Mashhad. This city is the second biggest city of Iran, a dense metropolitan area which is sprawling fast (Fig. 14). Given the existence of the well-known urban heat island phenomenon (UHI), this strong urbanization might contribute to additional warming at this location. As the land use is kept constant during the climate runs, the local effect of urbanization is not present in the modelled climate, which might explain the slower rate of heating of the model in Mashhad.



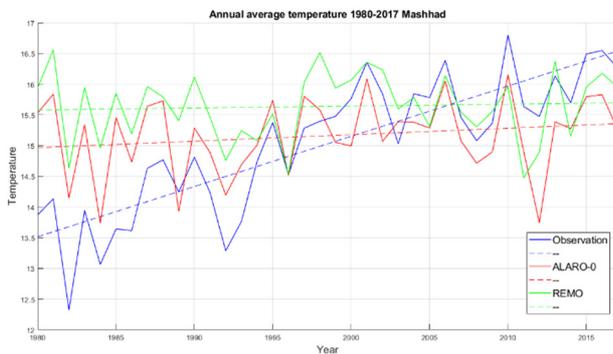
**Fig. 11.** Annual temperature comparison. Shiraz.

The urban heat island (UHI) mainly affects the minimum daily temperature in comparison with average or maximum daily temperature (Fig-14,16), so the trend slope for daily minimum temperature is sharper in comparison with daily maxima; besides, being located in a valley between two high mountain has caused less air

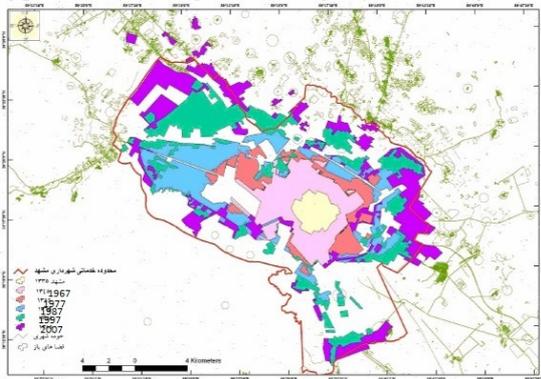
circulation with other areas, and perhaps it can amplify the impact of UHI on temperature.



**Fig. 12.** Annual mean temperature comparison. Tabriz.

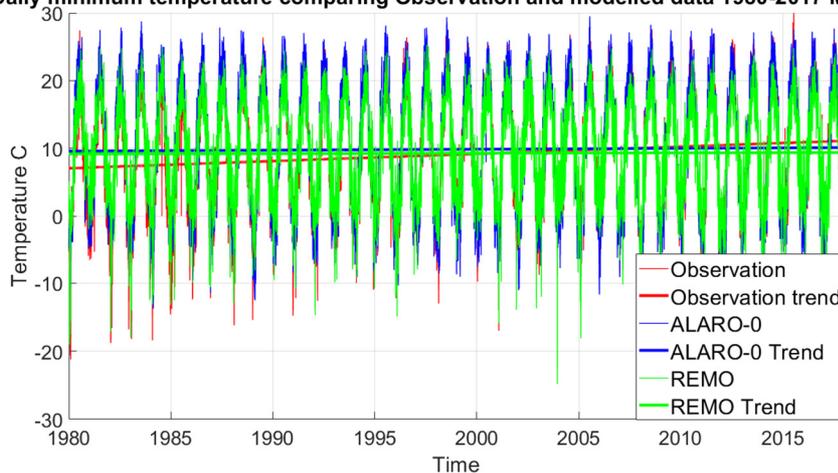


**Fig. 13.** Annual temperature comparison. Mashhad.



**Fig. 14.** Mashhad expansion map, 1967-2007

**Daily minimum temperature comparing Observation and modelled data 1980-2017 Mashhad**



**Fig. 15.** Daily minimum temperature.

### 2.1.2 Vapor pressure & Relative humidity Analysis

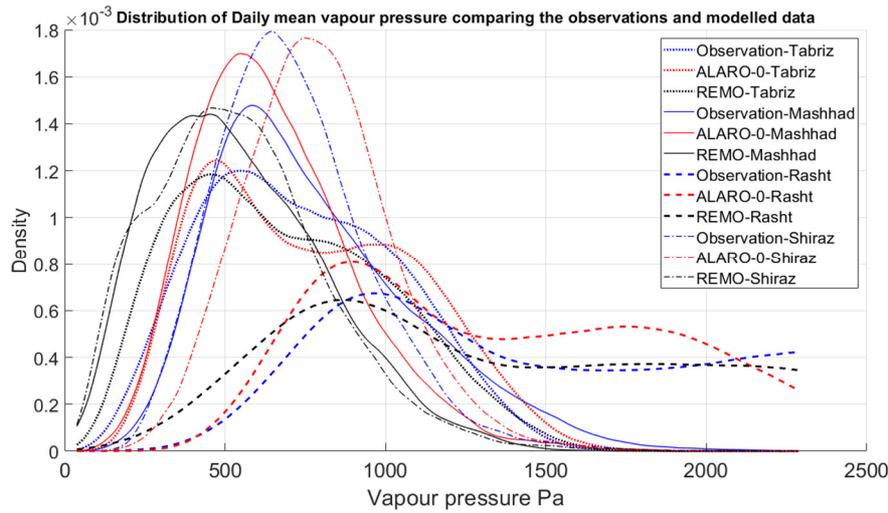
Some of the conclusions of the previous section (on temperature) will return in the RH and vapor pressure analysis as these parameters are closely related to temperature.

The distribution and annual charts of relative humidity represent some remarkable results about the reliability of the models in this parameter. Except for Rasht, which is the most humid location in the region, an acceptable level of reliability can be observed for both models, but the ALARO-0 model almost over the region shows the better results (Table 3). The reliability of both models in vapor pressure parameter is less (Table 3), and unlike the results in the RH parameter, over all locations, the REMO model gets a better score (Table 3, Fig. 16).

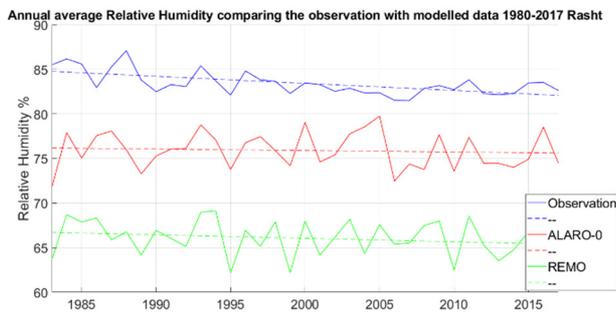
**Table 3.** Validation coefficients

Vapour pressure (daily)	Alaro-0 Model		REMO model	
	Correlation	Adjusted R-Squared	Correlation	Adjusted R-Squared
Mashhad	0.74	0.70	0.78	0.72
Rasht	0.78	0.69	0.78	0.69
Tabriz	0.86	0.81	0.96	0.89
Shiraz	0.61	0.92	0.67	0.67
RH (monthly)				
Mashhad	0.89	0.80	0.83	0.69
Rasht	0.74	0.54	0.46	0.22
Tabriz	0.90	0.81	0.82	0.68
Shiraz	0.95	0.92	0.82	0.67

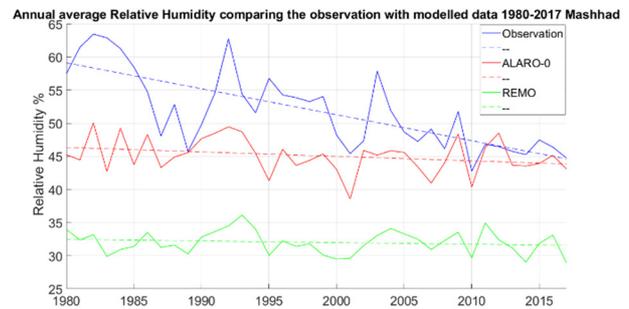
Analyzing the REMO model RH values shows a significant underestimation almost in all locations (Fig. 17), whereas the analysis results of vapor pressure values show that the REMO model is more accurate and reliable (Table 3, Fig. 16). The study of annual charts indicates that the trend of both models following the observations during the studied period over all stations is descending.



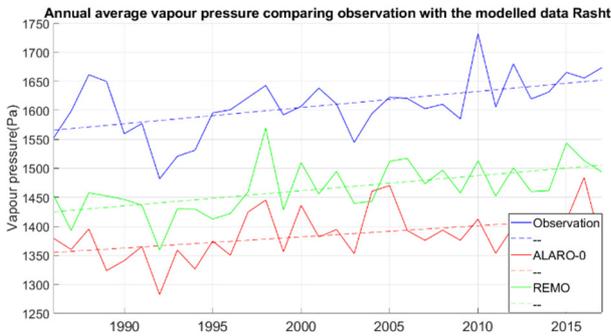
**Fig. 16.** Distribution of daily mean vapour pressure values



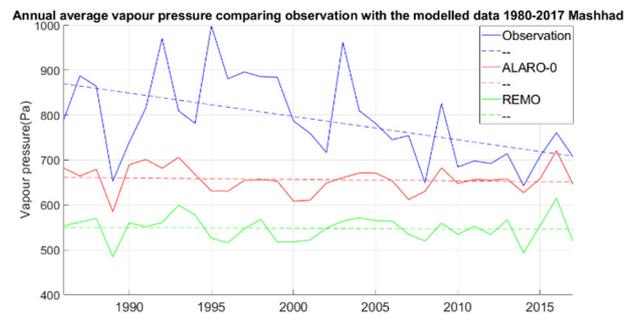
**Fig. 17.** The yearly average of RH. Rasht.



**Fig. 19.** The annual average of relative humidity. Mashhad.



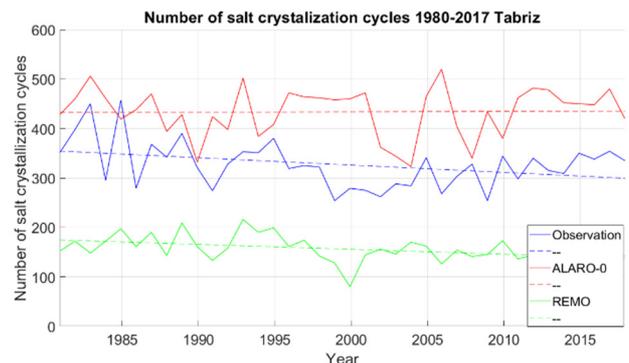
**Fig. 18.** The annual average of vapor pressure. Rasht.



**Fig. 20.** The annual average of vapor pressure. Mashhad.

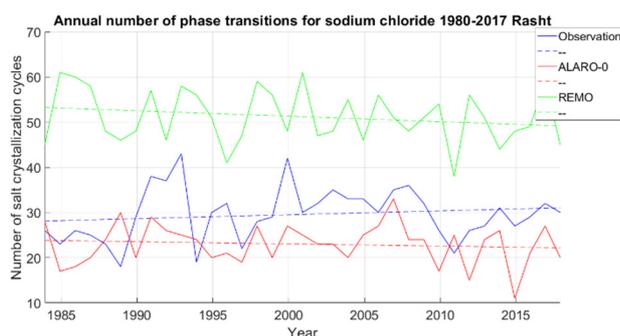
Analyzing the annual graphs of both parameters indicates that despite the overestimation or underestimation of the models, the trend slope of both models is consistent with the observations. In relative humidity charts, all datasets follow a descending slope, and as a result (considering temperature trends), the slope of graphs in vapor pressure analysis is ascending (Fig. 18). Once again, in Mashhad, we can observe the different results. The slope of the observation values is considerably more descending, and unexpectedly, in vapor pressure graphs, the trend is descending too (Fig. 19, Fig. 20). As it has been noted in the previous chapter, the urban heat island (UHI) effect, perhaps is responsible for such a tremendous difference, as Chinese researchers have concluded that there is a sharper decrease in RH and unusual decrease in vapor pressure with the effect of urbanization [6].

Salt weathering is an excellent example of damage driven by a phase change and is dependent on the local climate [7]. This damage arises during the crystallization–dissolution cycles, which occur under precise thermo-hygrometric conditions. Some non-hydrated salts, such as



**Fig. 21.** Number of salt crystallization cycles – Tabriz

sodium chloride, crystallize at a fixed humidity virtually independent of temperature, whereas phase transitions in hydrated salts, such as sodium sulfate, are always sensitive to both relative humidity and temperature. The number of phase transitions was used as a method for estimating potential salt damage [8,9]. In the case of the non-hydrated salt, sodium chloride (halite, NaCl), this was assessed by counting the number of times the average daily relative humidity crossed the critical deliquescence point of 75.3% for Sodium chloride on consecutive days. Only the transitions that occurred when the humidity was decreasing, and crystallization occurs, were counted, but this is equivalent to the number of cycles. Thus the number of transitions is virtually the number of crystallization–dissolution cycles [10]. These cycles have been calculated for both models and observations over the region and indicate that during the studied period, the number of cycles in Tabriz, Shiraz, and Mashhad has been decreased (Fig. 21), and both models successfully predicted the similar trend with the observation. Whereas in Rasht we can observe an incremental trend in the number of cycles, and this item could be counted as a threatening factor in heritage pathology over the area, but both models, unlike the observations, have predicted a slight decrease in salt crystallization cycles (Fig. 22).



**Fig. 22.** Number of salt crystallization cycles - Rasht

### 2.1.2 Precipitation Analysis

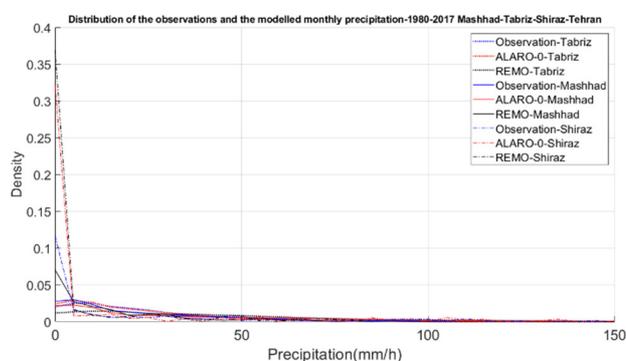
The distribution and validation coefficients of the total monthly precipitation indicate that there is an acceptable level of consistency between both models and the observations during the studied period, but the ALARO-0 model is more accurate (Table 4, Fig. 23). The study of distribution graphs consists of interesting and considerable results where the REMO model, in comparison with the ALARO-0, shows a high level of oscillation and mismatch almost in all locations (Fig. 23, Fig. 24). The resolution of the observed and modelled data is different. Whereas measurements have a resolution of 0.1 mm, modelled data can specify precipitation amounts in the order of 1e-34. Therefore, precipitation amounts smaller than 0.1 mm are removed from the modelled dataset. The frequency of light rainfall is generally overestimated by the ALARO-0 model in more rainy locations like Tabriz and Rasht, whereas in these locations the REMO model has considerably overestimated the frequency of light precipitation in Mashhad and Rasht. The ALARO-0 model underestimates the higher

precipitation frequency in more rainy locations, and again a considerable underestimation can be observed in the REMO model over Mashhad and Rasht.

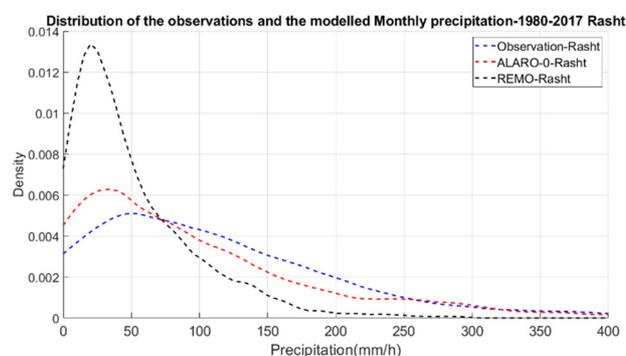
A significant point to be observed in the annual graphs is the noticeable difference between REMO and observations which is mostly and considerably underestimated by the REMO whereas, except Rasht where the ALARO-0 model has an incremental trend, generally the ALARO-0 model shows an acceptable level of consistency with the observations (Figs. 24-27).

**Table 4.** Models statistic results (Total Monthly Precipitation).

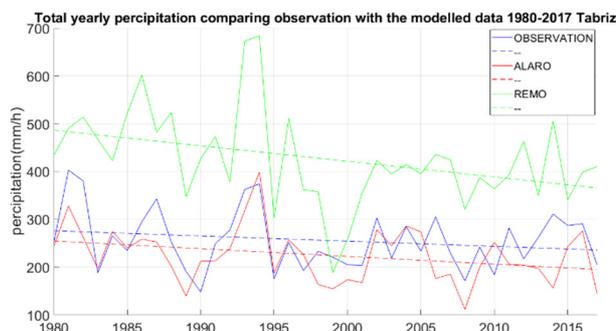
Precipitation	Alaro-0 Model		REMO model	
	Correlation	Adjusted R-Squared	Correlation	Adjusted R-Squared
Mashhad	0.78	0.61	0.72	0.52
Rasht	0.76	0.57	0.69	0.48
Tabriz	0.71	0.50	0.65	0.42
Shiraz	0.89	0.79	0.85	0.73



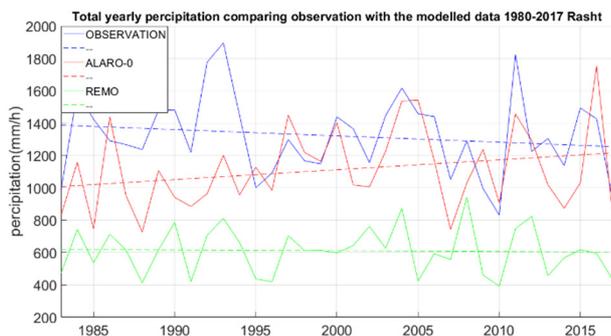
**Fig. 23.** Distribution of monthly precipitation. MashhaTabriz.



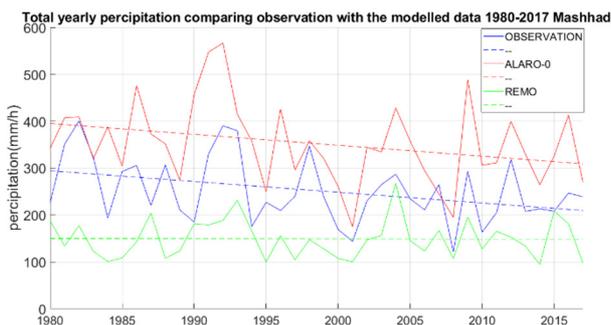
**Fig. 24.** Distribution of total monthly precipitation. Rasht.



**Fig. 25.** The total yearly precipitation plot. Tabriz.



**Fig. 26.** The annual total precipitation chart. Rasht.



**Fig. 27.** The annual total precipitation chart. Mashhad.

### 3 CONCLUSION

Regarding previous analysis, figures, and statistics, it is clear that both models have their strengths and weaknesses. In general, the ALARO-0 model seems to have a better performance over Iran for most of the meteorological parameters. Especially at the Rasht location, the REMO model seems to have difficulties in reproducing this humid, subtropical climate. The observational temperatures series in Mashhad shows a striking temperature increase, which is not reproduced by the models. Probably this can be understood by considering an intensification of the urban heat island phenomenon at this measurement location explained by the strong urbanization in Mashhad. Concerning the relative humidity, the REMO model is significantly too dry, whereas the ALARO-0 model shows more realistic values. The analysis of critical parameters for building pathology like freeze-thaw cycles and salt crystallization illustrates that RCM model output is valuable, but care should be taken. It can be concluded that an evaluation study to understand the weaknesses and strengths of RCMs is essential before using these models to assess the impact of climate change on heritage. To improve the quality of the impact study, one should consider using bias-correction methods for the RCM data and using multi-model ensembles to assess the uncertainty.

The RCM runs used in this paper have performed in the context of the AFTER project, which is granted by the ERA.Net RUS Plus Initiative, ID 166. The computational resources and services for the ALARO-0 regional climate simulations were provided by the Flemish Supercomputer Center (VSC), funded

by the Research Foundation-Flanders (FWO) and the Flemish Government department EWI. The CORDEX-CORE REMO simulations were performed under the GERICS/HZG share at the German Climate Computing Centre (DKRZ). We would like to thank Steven Caluwaerts (UGent), Lola Kotova (GERICS), and Sara Top (UGent) for providing climate data.

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